A SIMPLE FIGURE OF MERIT FOR HIGH TEMPERATURE SUPERCONDUCTING SWITCHES*

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Abstract

The discovery of the new high temperature superconductors has revived interest in many special applications, including superconducting switches. For comparison of switch types, a simple figure of merit based on switch performance is proposed, derived for superconducting switches, and then calculated for thyristors and vacuum switches. The figure of merit is then used to show what critical current density would be needed for superconducting switches to compete with more conventional switches.

Introduction

Conventional superconductors, with critical temperatures (T_C) below 20 K, have seen only limited application due to their need for liquid helium cooling (about 4 K). Therefore, the Bednorz and Muller announcement[1] in the fall of 1986 that superconductivity had been achieved at the "high" temperature of 35 K resulted in a surge of research and development efforts by scientists around the world. The possibility of having superconductors at liquid nitrogen temperature (77 K) was soon confirmed by Wu and others,[2] who observed a T_C of 95 K, and the new high temperature superconductors (HTSCs) quickly became the topic of numerous papers in the scientific journals and the popular press.[3-12]

The discovery and continued development of HTSCs have revived interest in many special superconductor applications. For example, superconducting switches are again being proposed as candidates for the "ideal switch," a switch that can operate without losses and change states almost instantaneously. However, superconducting switches are not ideal, as will be discussed. Some of the important issues affecting their development include the following:

1) A superconducting switch still has losses under some conditions;
2) Energy dissipated in the switch is absorbed by the cryogenic fluid and must be removed at a considerable penalty by the refrigerator;
3) The critical current density of the HTSCs is strongly reduced by the application of an external magnetic field; and
4) Attempts to make wire and cable reliably from HTSCs have not been very successful to date.

Before starting a major development program on superconducting switches, it would be very useful to have a simple method to determine the minimum performance needed from the HTSC materials before HTSC switches can begin to compete with other switch types. Therefore, the objectives of this paper are to develop a simple figure of merit (FOM) for electrical switches (including superconducting switches), to use the FOM to compare the effectiveness of HTSC switches with other switch types, and to obtain an indication of the improvement needed in the critical current density of HTSC material for HTSC switches to be viable.

Background

This paper will not discuss the design and construction of HTSC switches; It is assumed that they will be similar to those previously built from low temperature superconductors.[13-14] Two issues important to the operation of superconducting switches, regardless of their construction details, are switch losses and the penalty of cryogenic operation.

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Superconducting Switch Losses

Unless the switch current is absolutely steady, a superconducting switch will have losses that cannot be avoided. AC losses occur in the superconductor whenever the current level changes and are due to breaking of the flux pinning forces as the magnetic flux changes inside the conductor.[14-15] High pinning forces, needed if a superconductor is to carry heavy current in the presence of a high magnetic field (as in coils and switches), result in high AC losses.[15]

Likewise, eddy current losses occur in the normal metal part of the superconducting cable whenever the current level changes.[14] Normal metal, such as copper, is used in parallel with the superconductor to provide mechanical strength and operational stability; It provides a safety bypass route for current flow should part of the superconductor go normal for any reason.

Finally, switching losses occur after the switch has changed from a superconducting state to a normal state. These losses are due to the switch having to "work" to open the circuit by generating a voltage to force the current out of the switch branch. These losses are directly related to the energy stored in the switch inductance and to the energy transferred to the inductance of the load.[16-18]

Penalty of Cryogenic Operation

Energy dissipated in the superconducting switch is absorbed by the cryogenic fluid and eventually must be removed by the refrigeration system. However, the process of moving heat between two temperature levels is limited by the Carnot cycle efficiency describing an ideal, reversible system.[14,19] Under such conditions, the work, W, required to take the heat, Q_1, dumped into the cryogenic fluid at temperature T_1 by the superconducting switch and reject it at room temperature, T_2, is given by

$$W = Q_1 * (T_2 - T_1)/T_1 \quad . \tag{1}$$

Therefore, for each joule of energy dissipated in the cryogen, an ideal (Carnot) refrigerator rejecting heat at room temperature (300 K) must expend:

a) For liquid helium operation:

$$1 \text{ J} * (300 \text{ K} - 4 \text{ K})/(4 \text{ K}) = 74 \text{ J} \quad \text{, and} \tag{2}$$

b) For liquid nitrogen operation:

$$1 \text{ J} * (300 \text{ K} - 77 \text{ K})/(77 \text{ K}) = 2.9 \text{ J} \quad . \tag{3}$$

After taking the operational efficiency of real refrigerators into account, up to 1000 J of work are required to absorb 1 J at liquid helium temperature and up to 40 J are required for 1 J at liquid nitrogen temperature.[20-22] Furthermore, the current leads which connect the superconducting switch to the room temperature environment represent a sizeable steady-state heat leak into the cryogen which must also be handled by the refrigerator.[23] Therefore, a sizeable advantage of the new HTSCs is that the refrigeration penalty for energy dissipated in the cryogen is only about 1/25th as severe for liquid nitrogen temperature as for liquid helium temperature. Nevertheless, it is still significant, especially for large systems.

Figure of Merit for Switches

A figure of merit (FOM) is defined as a performance rating that governs the choice of a device for a particular application.[24] A FOM for switches,

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14. ABSTRACT
The discovery of the new high temperature superconductors has revived interest in many special applications, including superconducting switches. For comparison of switch types, a simple figure of merit based on switch performance is proposed, derived for superconducting switches, and then calculated for thyristors and vacuum switches. The figure of merit is then used to show what critical current density would be needed for superconducting switches to compete with more conventional switches.

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therefore, should allow various switch types to be compared on a performance basis. A reasonable definition of the figure of merit for electrical switches, FOM_{SWITCH}, is proposed as the power handling capability of the switch per unit volume, or

$$FOM_{SWITCH} = POWER / VOLUME \quad , \tag{4}$$

$$= CURRENT * VOLTAGE / VOLUME \quad , \tag{5}$$

where CURRENT and VOLTAGE are the switch current and voltage ratings, respectively, and VOLUME is the volume of the switch.

HTSC Switches

The current rating of a HTSC switch is a function of the maximum operating current density, J_C, in the superconducting wire and is given by the expression:

$$CURRENT = J_C * AREA \quad , \tag{6}$$

where AREA is the cross sectional area of the wire or cable in the switch. Similarly, the voltage that a HTSC switch is able to generate when opening (by going to the normal state) is given by:

$$VOLTAGE = CURRENT * RESISTANCE \tag{7}$$

$$= (J_C * AREA) * (\rho_N * L / AREA) \tag{8}$$

$$= \rho_N * L * J_C \quad , \tag{9}$$

where ρ_N is the resistivity of the HTSC material in the normal state, and L is the length of conductor in the HTSC switch. Now from Eqs. (5)-(9), the FOM of a HTSC switch can be written as:

$$FOM_{HTSC} = CURRENT * VOLTAGE / VOLUME \tag{10}$$

$$= (J_C * AREA) * (\rho_N * L * J_C) / VOLUME \tag{11}$$

$$= (\rho_N * L * AREA * J_C^2) / VOLUME \quad . \tag{12}$$

But the switch volume is simply the product of the conductor length and area (L * AREA) so that the FOM for HTSC switches becomes

$$FOM_{HTSC} = POWER / VOLUME = \rho_N * J_C^2 \quad . \tag{13}$$

This relationship between power and volume for superconducting switches has been previously reported by others[14,25] but not in reference to a figure of merit.

High temperature superconductors have been produced from a number of materials in a variety of forms ranging from thin films and single crystals to polycrystalline bulk. Actual material properties vary considerably, depending on the specific manufacturing process. For example, the normal resistivity (just above T_C) of $YBa_2Cu_3O_{7-x}$, the most widely-studied HTSC (also known as 1-2-3 HTSC), varies from 8-17 mΩ-cm along the c-axis of single crystals,[26,27] to 1.5 mΩ-cm for a thick film,[28] to 250 μΩ-cm for melt-processed polycrystalline bulk,[29] to 200 μΩ-cm in the a-b plane of single crystals,[27,30,31] and finally down to about 80 μΩ-cm in the twinned a-b direction of a single crystal.[32] Likewise, the critical current density for 1-2-3 HTSC samples varies greatly, from a few hundred A/cm^2 for ordinary bulk samples (polycrystalline) to over 10 kA/cm^2 for single crystals (in the ab plane) and to the MA/cm^2 range for thin films.[5,9,15,30,33] Because it is too early in the development of HTSCs to know what specific performance parameters a successful conductor will have, the FOM for HTSC switches must be considered for a range of resistivity values.

Finally, as the packing factor of the cable is reduced from 100%, as occurs when normal metal is added in parallel with the superconductor for strength and stability, the FOM_{HTSC} is correspondingly reduced. For comparison with other types of high power opening switches (such as solid state thyristors, vacuum interrupters, and triggered vacuum gaps), we must first obtain their FOM based on performance ratings.

Thyristors

Solid state thyristor switches have become increasingly popular due to their reliability, lifetime, and ease of use. The best developed and most common type of thyristor, the silicon controlled rectifier (SCR) switch, is a unidirectional device that remains open until a trigger pulse is applied to the gate; It then remains conducting until the switch current goes through zero and a reverse voltage is applied long enough for the switch to recover or open.[34-36] Because of speed-versus-power design tradeoffs, thyristor switches are usually manufactured as one of two types, phase control or inverter (with turn-off time their major difference). Generally, phase control thyristors have turn-off times ranging from 250-700 μs while inverter thyristors have turn-off times ranging from 40-120 μs. The turn-off time usually increases with increasing device size and voltage rating.

Current ratings for thyristors are established for various conduction times to prevent burn-out under different operating conditions. Steady-state current limits are given in terms of both the average current and the RMS (effective DC) current. The peak current that can be carried in a short pulse depends on the silicon's maximum allowable current density and its upper temperature limit and can be 10-15 times the steady-state current rating. Short-pulse current limits are given by the half-cycle (8-ms), 3-cycle, and 10-cycle 60-Hz AC ratings.

To determine a typical FOM for thyristors, the FOM for the largest devices in a recent product catalog[37] were calculated. A 2000-V, 4800-A_{rms} phase control thyristor (type S77R20A) has a volume of 289 cm^3, giving a steady-state FOM of 47 kW/cm^3; With a half-cycle (8-ms) surge rating of 56 kA, it has a surge FOM of 388 kW/cm^3. Similarly, a 2000-V, 1500-A_{rms} inverter thyristor (type S52KF20B) has a volume of 98 cm^3, giving a steady-state FOM of 43 kW/cm^3; With a half-cycle surge rating of 20 kA, it has a surge FOM of 410 kW/cm^3. It should be noted that the switch volumes in these calculations do not include heat sinks, balancing networks, and related equipment needed for proper installation in an application.

Vacuum Interrupters

Mechanically-operated vacuum interrupters (VIs), switches used primarily in the electric utility industry, are good candidates for many high power opening switch applications for several reasons: they are able to conduct tens of kiloamperes, recover quickly (within 10-20 μs) following a current zero, and then withstand a recovery voltage of tens of kilovolts.[16,36,38-41] Compared to solid state thyristors, VIs are much less susceptible to damage from momentary voltage or current overloads and are considerably less expensive.

Vacuum interrupters have two planar or disc electrodes, one fixed and one movable, inside a vacuum envelope. The switch is closed when the electrodes are in contact. When the electrodes are separated by an external actuator, an arc is drawn between the contacts. The vacuum arc, sustained by evaporation of metal from the electrodes, deionizes quickly during the next current zero to allow switch recovery to the open state.

Vacuum interrupters have been used in pulsed power applications at the Los Alamos National Laboratory since the early 1970s. In a series of tests to determine the interruption capability of standard commercial devices under pulsed conditions (with a fast current counterpulse providing the current zero), the interruption limits for 50% and 90%

reliability were determined for conduction times of 5-10 ms (basically equivalent to the AC half-cycle thyristor ratings).[42,43] The surge FOM for various sized VIs can be calculated from these results. The best 5"-diameter VI was able to interrupt 17 kA with a reliability of 90% at a recovery voltage of 34 kV. With a volume of 3051 cm^3, the 5" VI had a surge FOM of 189 kW/cm^3. The best 7"-diameter VI interrupted 24 kA at 90% reliability at a recovery voltage of 48 kV. With a volume of 5528 cm^3, the 7" VI had a surge FOM of 208 kW/cm^3. Finally, a similar 7" VI with an axial magnetic field applied in the arc region was able to interrupt 37 kA (the test facility limit) and recover to 74 kV with no failures, giving it a surge FOM of at least 495 kW/cm^3.

Rod Array Triggered Vacuum Gaps

Triggered vacuum gap (TVG) switches are very similar in construction to vacuum interrupters except that the electrodes are fixed some distance apart and, therefore, require a trigger system to initiate the arc to close the switch.[16,36,44] Once the arc is established, the TVG switch remains closed until the next current zero allows the switch to recover (just as in VIs). While standard TVGs have interrupting capabilities well below that of VIs, a special type of TVG, the rod array triggered vacuum gap (RATVG) switch, has demonstrated current interruption performance well beyond that of any other type of vacuum switch. The RATVG switch was developed by the General Electric Company (GE) under contract to the Electric Power Research Institute for possible use in AC transmission systems.[45,46] Instead of disc electrodes as in standard TVGs, the RATVG switch has rod electrodes oriented axially and interleaved. After initiation by a trigger pulse, the arc burns in a circumferential direction between the rods.

In AC tests at GE, the best of the RATVGs, the type G1 switch, conducted an AC half-cycle current pulse of 150 kA_{peak}, interrupted at current zero, and recovered to 135 kV. These results were facility limited--the true interruption limits are not known. Therefore, with a volume of 25,740 cm^3, the G1 switch has a surge FOM of at least 787 kW/cm^3, more than twice that of the axial-field-assisted VI.

Comparison of Results

With the determination of the FOMs for thyristors, vacuum interrupters, and rod array triggered vacuum gaps, it is easy to make a comparison with the FOM for HTSC switches. Recall that the FOM_{HTSC} varies with $\rho_N*J_C^2$, and that the normal resistivity of present HTSC material varies over several orders of magnitude. Because it too early to predict what the resistivity of a HTSC wire or cable will be, the FOM_{HTSC} must be plotted for a range of resistivity values.

Therefore, the FOM for HTSC switches, as obtained from Eq. (13), is plotted in Fig. 1 as a function of J_C for 3 different resistivity values (10, 1, and 0.1 mΩ-cm) The effects of reduced packing factors are shown for the 10 mΩ-cm case. For comparison, the FOMs for conventional switches are also shown. Recall that the FOM for thyristors was about 50 kW/cm^3 for the steady-state case and over 400 kW/cm^3 for the pulsed-duty case while the pulsed-duty FOM for vacuum interrupters was nearly 500 kW/cm^3 and for the rod array triggered vacuum gap almost 800 kW/cm^3.

Conclusions

The results of Fig. 1 show that a HTSC switch would need an operating critical current density of at least a few kA/cm^2 but more likely 10-100 kA/cm^2, depending on actual switch construction details and resistivity, to begin to be competitive with more conventional switch types. It should be emphasized that this comparison is based on the switching action FOM (power/volume) for the switch volume itself and

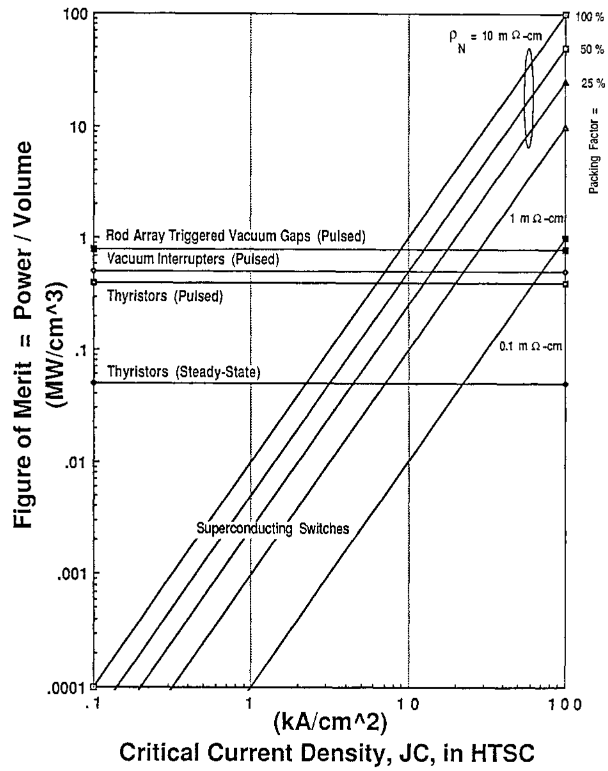

Fig. 1. Graph showing the figure of merit for HTSC and conventional switches.

does not take into account any auxiliary equipment needed (refrigerators, heat sinks, balancing networks, counterpulse capacitor banks, etc.). Neither does it consider other important factors such as switching speed, conduction drop during steady-state operation, or costs. Therefore, a more accurate comparison must await further developments from research into HTSC materials and the manufacture of HTSC wires and cables

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